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Medicinal Product for the Promotion of Wound Healing

This invention relates to a medicinal product for topical use for the promotion of wound healing.

It is known that the healing of a wound progresses in several successive stages.

In stage I, the blood plasma protein fibrinogen is precipitated by thrombin so as to induce the formation of a fibrin clot, which solidifies in the presence of blood coagulation factor XIII. In the first stage which takes only minutes bleeding is controlled and the wound area is sealed.

In stage II, cells from the wound area migrate into the fibrin clot, i.e., inflammatory cells, connective tissue cells and endothelial cells. They form vessels and, as an extracellular matrix, connective tissue primarily comprised of collagen. This connective tissue, which is referred to as granulation tissue, serves as the substratum for the formation of epithelial tissue and is the substratum for the epidermis on the body surface. Stage II lasts for days to weeks and is complete as soon as the wound area has been closed by epithelium, and by the epidermis on the skin.

Wound healing is complete by stage III, which lasts for weeks to months. During that phase, the cellular elements are reduced and the connective tissue is growing so as to form a firm and permanent scar tissue. (Bennett N.T., Schultz G.S., Am. J. Surg. 1993, 165:728-737; Bennett N.T., Schultz G.S., Am. J. Surg. 1993, 166: 74-81).

The formation of granulation tissue in stage II of the wound healing process is effected by growth factors promoting the migration and the division of connective tissue cells as well as the regeneration of vessels and, thereby, accelerating wound healing. Of the known growth factors, platelet derived growth factor (PDGF), transforming growth factor β (TGF-β), epidermal growth factor (EGF) and insulin-like growth factor I (IGF-I) are particularly involved in those processes. (Bennett N.T., Schultz G.S., Am. J. Surg. 1993, 165: 728-737; Bennett N.T., Schultz G.S., Am. J. Surg. 1993, 166: 74-81; Bhora F.Y. et al., J. Surg. Res. 1995, 59: 236-244; Lynch S.E. et al., Proc. Natl. Acad. Sci. USA 1987, 84: 640-646; Lynch S.E. et al., J. Clin. Invest. 1989, 84: 7696-7700).

Also the regeneration of the epidermis is induced by growth factors. They activate the epidermal cells (keratinocytes) that have been detached from the cell association of the intact basal cell layer due to the lesion, so as to form specific membrane receptors enabling the

adherence to the granulation tissue substratum, in particular to fibrin-fibronectin, which constitutes a provisional scaffold for keratinocyte migration (Brown G.L. et al., J. Exp. Med. 1986, 163: 1319-1324; Brown G.L. et al., N. Engl. J. Med. 1989, 321: 76-79).

Growth factors are synthesized in the human body by various tissues and cell types and secreted into the surrounding body liquid. In the context of wound healing, an important regulatory role is attributed to thrombocytes, which are able to synthesize in significant amounts and store growth factors PDGF, TGF-β, EGF and IGF-I, which are essential to wound healing in cytoplasmic granula. (Lynch S.E. et al., Proc. Natl. Acad. Sci. USA 1987; 84: 640-646; Ginsberg M.H. et al., Thromb. Haemostas. 1988, 59: 1-6; Hyner O.R., Thromb. Haemostas. 1991, 66: 40-43).

In order to release or deliver the stored growth factors from the thrombocytes, the latter must be activated by physiological stimuli such as, e.g., collagen, thrombin, trypsin, ADP, serotonin or adrenalin, which bind to specific receptors on the external surface of the thrombocyte plasma membrane. Activation results in a change of shape followed by the aggregation of thrombocytes, whereupon the latter secrete the stored growth factors into the surrounding body liquid. With most of these physiological stimuli, the aggregation of thrombocytes following activation is a prerequisite for the release of growth factors. By stimulation with thrombin, growth factors may be released also without thrombocyte aggregation. (Kaplan K.L. et al., Blood 1979, 53: 604-618; Holmsen H. et al., J. Biol. Chem. 1981, 256: 9393-9396; Philipps D.R., Baughan A.K., J. Biol. Chem. 1983, 258: 10240-10245).

The interactions between activated thrombocytes, which lead to aggregation, and their adherence to surfaces are mediated by extracellular adhesive matrix proteins such as, e.g., fibrinogen, fibronectin and von Willebrand factor, which bind to a glycoprotein receptor on the external side of the plasma membrane of the activated thrombocytes. Strong binding of these matrix proteins to the receptor is effected only where thrombocytes have been activated by an appropriate stimulus as described above. These complex procedures of thrombocyte activation and aggregation followed by the release of growth factors constitute one of the essential control elements in the wound healing process. (Ginsberg M.H. et al., Thromb. Haemostas. 1988, 59: 1-6; Hyner O.R., Thromb. Haemostas. 1991, 66: 40-43; Landolfi R. et al., Blood 1991, 78: 377-381; Perschke E.I. et al., Blood 1980, 55: 841-847; Hynes O.R., Cell 1992, 69: 11-25; Perschke E.I., J. Lab. Clin. Med. 1994, 124: 439-446; Savage B.,Ruggeri Z.M., J. Biol. Chem. 1991, 266: 11227-11233; Bennett J.S. et al., J. Biol. Chem. 1982, 257:

8049-8054; Cierniewski C.S. et al., Biochim. Biophys. Acta 1982, 714: 543-548; Philipps D.R., Baughan A.K., J. Biol. Chem. 1983, 258: 10240-10245).

Disturbances in wound healing as these occur, for instance, in patients with diabetes, venous or arterial occlusions, but also wound healing disturbances of other geneses such as, for instance, irradiation with radioactive substances or after burns particularly affect stage II of the wound healing process. It has been found that in such cases growth factors are present to a reduced extent so that no or only a low quality granulation tissue is formed. (Dvonch V.M. et al., Surgery 1992, 112: 18-23; Matsuoka J., Grotendorst G.R., Proc. Natl. Acad. Sci. USA 1989, 86: 4416-4420).

In order to enhance wound healing in the case of wound healing disturbances, growth factors are known to be applied to the wound area, either individually or in combination, as a pure substance or mixed in ointment bases (Knighton D.R. et al., Surg. Gynecol. Obstet. 1990, 170: 56-60; Brown G.L. et al., J. Exp. Med. 1986, 163: 1319-1324; Holmsen H. et al., J. Biol. Chem. 1981, 256: 9393-9396). The growth factors provided in this manner are, however, rapidly inactivated or degraded and develop their activities only over short periods of time (minutes) after application. Thus, these preparations offer no satisfactory enhancement of wound healing.

Other known therapeutic approaches consist in covering the wound area with collagen sponges or other preparations aimed to ensure permanent humidity of the wound area or in using preparations degrading the superficial connective tissue layer of the wound area by fermentation so as to enable new connective tissue to re-grow from the wound bed (Nielsen P.G. et al., Acta Dermato-Venerologica 1990, Suppl. 152: 1-12; Lippert P., Wolff H., Zent.bl. Chir. 1990, 115: 1175-1180). Yet, none of those hitherto applied wound dressings and preparations or medicinal products have brought satisfactory results in improving wound healing.

The object of the present invention is to provide a medicinal product which efficaciously accelerates natural wound healing processes and is capable of substantially improving wound healing where wound healing is disturbed, in particular in severe forms of wound healing disturbances, as compared to conventional therapies.

In accordance with the invention, this object is achieved in that a medicinal product for topical use for the promotion of wound healing is provided, which comprises thrombocytes or thrombocyte fragments, wherein said thrombocytes or thrombocyte fragments contain growth

factors and are capable of releasing the same, are present in the lyophilized or deep-frozen state and have been subjected to a process for virus partitioning and/or virus inactivation.

"Thrombocyte fragments" is intended to denote any insoluble thrombocyte constituents that are separable from the soluble thrombocyte constituents either by filtration including nano-filtration or by centrifugation including ultracentrifugation.

Unless indicated otherwise, the term "thrombocytes" in the following also encompasses "thrombocyte fragments".

The invention is based on the finding that the topical use of thrombocytes containing growth factors and capable of releasing the same can efficaciously accelerate wound healing processes. The thrombocytes applied on the wound area constitute a natural reservoir for the growth factors required for the promotion of the wound healing processes. It has been found that the activation of locally applied thrombocytes by physiological stimuli present in the wound area and the subsequent aggregation and binding of the matrix proteins present in the wound area lead the growth factors stored in the thrombocytes to be released into the wound area continuously over an extended period of time (several days). Due to this fact, higher concentrations of growth factors are apparently available in the wound area over a substantially longer period of time than with the direct administration of growth factors, thereby promoting the immigration of inflammatory cells, connective tissue cells and endothelial cells and enhancing the propagation of said cells in stage II of the wound healing process. In that manner, the rapid and sufficient formation of granulation tissue is ensured, which, in turn, renders possible the formation of epithelial tissue and the final wound closure. The epithelization process, moreover, is additionally accelerated by the released growth factors promoting the immigration and proliferation of epithelial cells.

To ensure that the medicinal product can be stored over an extended period of time, the thrombocytes in the medicinal product according to the invention preferably are present in the lyophilized or deep-frozen state. In order to minimize the risk of virus infections, the thrombocytes advantageously are subjected to a process for virus partitioning and/or virus inactivation, whereby a physical or a chemical or a combined process may be used.

In order to provide for a higher concentration of growth factors, in particular in the treatment of wound healing disturbances, it is preferred that the content of thrombocytes or thrombocyte fragments of the medicinal product according to the invention is such that it corresponds to at

least 10^4, preferably at least 10^5, thrombocytes per µl after reconstitution of the lyophilisate or thawing.

In order to obtain a particularly pronounced initial effect of the medicinal product according to the invention immediately upon application, it may be appropriate, in particular in the case of severe disturbances of wound healing, that the medicinal product comprises additional growth factors that are not derived from the thrombocytes contained in the medicinal product. The additional growth factors may be of the same type as those stored and released by the thrombocytes of the medicinal product according to the invention or belong to a different type. The growth factors may be present in the same container with the thrombocytes or contained in a separate container in the form of a solution or lyophilisate.

It has been found that it is advantageous, in particular in severe cases of disturbed wound healing, that the medicinal product comprises biomaterials. "Biomaterials" in the sense of the invention is intended to comprise any materials which are tissue-compatible and absorbable and assist in the promotion of wound healing either in combination with the thrombocytes or growth factors contained in the medicinal product or independently thereof. Thus, substances activating thrombocytes as stimuli and/or materials mediating thrombocyte aggregation may be contained as biomaterials in the medicinal product according to the invention. In that manner, the activity of natural substances present in the wound area which activate thrombocytes and mediate their aggregation is enhanced, which increases the release of growth factors and promotes wound healing even further.

In order to minimize the risk of virus infections, the biomaterials preferably are subjected to a process for virus partitioning and/or virus inactivation, wherein a physical or chemical process or a combined process may be applied. The biomaterials may be subjected to such a process either individually or mixed with other components of the medicinal product (e.g., thrombocytes).

To ensure that the medicinal product can be stored over an extended period of time, the biomaterials in the medicinal product according to the invention advantageously are present in the lyophilized or deep-frozen state. In that case, the biomaterials may be present in the same containers with the thrombocytes and/or growth factors or contained in separate containers and deep-freezing or lyophilization of the biomaterials may be effected individually or in mixture with other components of the medicinal product.

It is known that the activation and aggregation of thrombocytes and hence the release of growth factors stored in the thrombocytes is enabled by the attachment of matrix proteins. Moreover, such proteins may form cross-linked structures to which the thrombocytes adhere and firmly bind to the wound area, such structures promoting the diffusion of growth factors to the wound area and the immigration of cells from the wound area. Accordingly, a preferred embodiment of the medicinal product according to the invention is characterized in that tissue adhesive and/or collagen are provided as biomaterials. Tissue adhesive in the sense of the invention is intended to encompass biomaterials totally or partially consisting of cross-linkable proteins suitable for tissue adhesion.

Fibrinogen is a particularly active substance for triggering the aggregation of activated thrombocytes, while thrombin represents one of the most active substances for the activation of thrombocytes. It is, therefore, advantageous for an increase in the relase of growth factors and an enhancement of wound healing that the tissue adhesive is composed of fibrinogen-containing proteins and thrombin.

It has been shown that human cells such as keratinocytes, epithelial cells, embryonic and fetal cells as well as cell constituents such as liposomes are able to additionally accelerate thrombocyte-promoted wound healing and cell propagation. It is, therefore, preferred that the medicinal product additionally comprises epithelial cells and/or keratinocytes and/or embryonic and/or fetal cells and/or liposomes. The cells or the liposomes may be present as a liquid or deep-frozen suspension or as a lyophilisate in separate containers, or one or several of the mentioned cell types or liposomes either without or with any of the other components of the medicinal product in common containers.

In order to minimize the risk of virus infections, the cells or the liposomes may have been subjected to a process for virus partitioning and/or virus inactivation, whereby a physical or a chemical process or a combined process may be used. The cells or the liposomes may be subjected to such a process either individually or mixed with other components of the medicinal product.

The invention also relates to the use of thrombocytes or thrombocyte fragments containing growth factors for the production of a medicinal product for topical use for the promotion of wound healing.

Preferred embodiments of the invention will now be explained in more detail by way of examples.

Example 1: Preparation of a medicinal product according to the invention

A human thrombocyte concentrate or concentrate of thrombocyte constituents is anticoagulated by 3 % sodium citrate and centrifuged (1000 g/20 min) in order to eliminate plasma and other cell constituents. The thrombocyte-rich supernatant, or supernatant of thrombocyte constituents, is suspended in RPMI medium and washed three times in RPMI medium (1000 g/20 min). The washed thrombocytes, or the washed thrombocyte constituents, are suspended in RPMI medium and adjusted to a concentration of at least $6x10^5$ thrombocytes or thrombocyte constituents per µl. After this, the thrombocyte suspension is subjected to a virus inactivation process according to Example 3 and subsequently deep-frozen or lyophilized in accordance with the methods described below, thereby obtaining a medicinal product according to the invention.

Deep-freezing: 1 ml of the thrombocyte suspension is each shock deep-frozen at -80° C within 30-40 minutes and stored in a deep-frozen state. Before use, the thrombocyte concentrate is thawed at room temperature.

Lyophilization: 1 ml of the thrombocyte suspension is each shock deep-frozen at -80° C for at least 24 hours and subsequently lyophilized at -20° C to -40° C *in vacuo* for 20 to 24 hours. The lyophilized thrombocytes are stored at between -20° C and -80° C and rehydrated with 1 ml RPMI medium before use.

Example 2: Preparation of a medicinal product according to the invention comprising biomaterials

The virus-inactivated thrombocyte suspension prepared according to Example 1 is supplemented with a solution of cross-linkable human protein (either fibrinogen, fibronectin, blood coagulation factor XIII or collagen) which may have been subjected to one or several processes for virus inactivation according to Example 4, each protein type separately or together in combination, wherein the concentration of the cross-linkable protein types in the supplemented solution preferably is to amount to 70-90 mg/ml. The mixing ratio of the thrombocyte suspension to the solution of cross-linkable human protein preferably is to be 1:3. The thus obtained mixture is deep-frozen or lyophilized in accordance with the processes described in Example 1 in order to obtain suitable storability.

Instead of carrying out virus inactivation on individual components (thrombocytes or biomaterials), it is also possible to effect virus inactivation on a mixture of thrombocyte suspension and protein solution according to the process of Example 3.

Example 3: Virus inactivation of thrombocyte suspension (photodynamic virus inactivation)

To 50 ml of the thrombocyte suspension prepared according to Example 1 is added 8-methoxypsoralen (dissolved in dimethylsulfoxide [DMSO]) until a final concentration of 300 µl/ml (final concentration of DMSO 0.3 %) and irradiated with ultraviolet light from below and above for 6 hours at 22-27°C under an atmosphere of 5 % CO_2 and 95 % N_2 and at a pressure of 2 psi such that the overall light intensity is 3.5 to 4.8 mW/cm^2 (Lin L. et al., Blood 1989, 74: 517-525).

After photoinactivation has been completed, the thrombocyte suspensions obtained in that manner are examined for their functional capacities. The functional capacity is determined by measuring [^{3}H]-thymidine incorporation in a fibroblast cell culture.

Example 4: Virus inactivation of biomaterials (chemical virus inactivation)

Biomaterials which are admixed to the thrombocyte suspension prepared according to Example 1 are virus inactivated by a solvent detergent method. To this end, a biomaterial suspension is supplemented with 1 % (w/w) tri(n-butyl) phosphate and 1 % (w/w) Triton X-100 at 30° C and the mixture is kept for 4 hours under shaking. After this, the solvent detergent mixture under the addition of 5 % (v/v) soybean oil is removed from the biomaterial suspension by chromatography on a C18-column (Waters Millipore) (Horowitz B. et al., Blood 1992, 79: 826-831; Piet M.P.J. et al., Transfusion 1990, 30:591-598; Piquet Y. et al., Vox sang. 1992, 63: 251-256).

The biomaterials treated by the above-described chemical virus inactivation method may subsequently be subjected to photodynamic virus inactivation in addition.

Example 5: Evaluation of the promotion of connective tissue proliferation by the medicinal product according to the invention

The test was carried out on a fibroblast cell culture. The medicinal product prepared according to Example 2 was applied on a cell culture plate in an amount of 200 µl per cm^2 and activated by 50 µl of a thrombin solution (3.2 IU thrombin per ml physiological saline). Human

fibroblasts derived from the 4^{th} to 10^{th} passages of a primary culture were placed on the applied suspension at a density of $4x10^4$ cells per cm^2 and cultivated in cell culture medium (RPMI) (culture 1). On the third, fifth and seventh days of cultivation, the cell mitotic rate was measured by measuring DNA synthesis via $[^3H]$-thymidine incorporation. The cell mitotic rate of culture 1 was compared to the cell mitotic rate of another fibroblast culture (culture 2) realized in RPMI nutrient supplemented with 10 % by vol. of calf serum without addition of the medicinal product according to the invention.

Results: On day 3 of cultivation, culture 1 exhibited a $[^3H]$-thymidine incorporation (196645±56864 cpm/ml) that was seven times higher than that of culture 2. On days 5 (152749±93951 cpm/ml) and 7 (77045±27974 cpm/ml) $[^3H]$-thymidine incorporation in culture 1 still was 5 to 10 times higher than that of culture 2. These differences between culture 1 and culture 2 statistically are highly significant ($p<0.01$), demonstrating the ability of the medicinal product according to the invention to promote connective tissue proliferation and maintain that activity over an extended period of time (at least 7 days).

Example 6: Evaluation of the binding of matrix proteins to thrombocyte surfaces resulting in the thrombocyte stored growth factors to be continuously released

The test was carried out on a fibroblast culture (according to Example 5). Culture 1 - as in Example 5 - was supplemented with the medicinal product according to the invention. In culture 2, the thrombocytes were treated with specific antibodies against the superficial binding sites for matrix proteins so as to prevent the matrix proteins from binding to thrombocyte surfaces. On the third day of cultivation, the cell mitotic rate was measured by measuring DNA synthesis via $[^3H]$-thymidine incorporation.

Results: While culture 1 exhibited a thymidine incorporation rate similar to that of Example 5, no thymidine incorporation could be measured in culture 2. That difference proves that the binding of matrix proteins to the thrombocyte surfaces is necessary for the thrombocyte stored growth factors to be released.

Example 7: Evaluation of the promotion of wound healing by the medicinal product according to the invention

The clinical efficacy of the medicinal product according to the invention was studied in six patients suffering from chronic, non-healing cutaneous ulcera of the lower extremities and already treated by surgical or conservative topical therapies for more than six months without

success. The ulcera were classified using a wound score according to Knighton D.R. et al., Ann. Surg. 1986, 204:322-330. The wound score includes general parameters, anatomical conditions and measurable variables of the ulcus. The higher the scores, the poorer the preconditions for healing; the highest score to be reached is 97 (= worst starting situation).

Treatment plan:

The ulcera were cleaned, necrotic tissue was removed and wetted with a thrombin solution (3.2 IU bovine thrombin/ml RPMI medium). After this, the defect was filled up with the thawed medicinal product according to the invention prepared according to Example 2, and the above-mentioned thrombin solution was then applied at a volume ratio of medicinal product suspension to thrombin solution of 3:1 in order to activate the thrombocytes. The ulcera treated in that manner were covered by a non-adhering wound dressing (metal foil). Until healing, the ulcera were treated twice a week in the above-identified manner. The healing progress was documented photographically and histologically (fine needle biopsies in the 2nd and 5th weeks of treatment).

Results:

The demographics, causative vascular and metabolic diseases of the patients and the evaluation of the wound scores at the beginning of treatment are summarized in Table 1.

Table 1

Patient	Sex	Age	Vascular Disease arterial	Vascular Disease venous	Metabolic disease	Wound Score
1	male	67	+	+	diabetes	51
2	male	72	+	-	-	65
3	male	69	+	-	diabetes	33
4	male	63	+	-	diabetes	49
5	male	78	+	+	diabetes	63
6	female	74	-	+	-	65[a]/63[b]

[a,b]) two ulcera on one leg: [a]) proximal, [b]) distal ulcus

The time course of wound healing (indicated in weeks as of the beginning of treatment) is illustrated in Table 2.

Table 2

Patient	Beginning of Granulation Tissue Formation	Beginning of Epithelization	Completion of Epithelization
1	1st week	3rd week	8th week
2	1st week	3rd week	9th week
3	3rd week	8th week	12th week
4	1st week	4th week	10th week
5	1st week	none	none
6	[a,b]1st week	[a]6th/[b]3rd week	[a]12th/[b]9th week

[a,b]) two ulcera on one leg: [a]) proximal, [b]) distal ulcus

With the exception of patient 3, a granulation tissue well supplied with blood formed starting from the bottom of the ulcus in all of the patients already within the first week of treatment, which granulation tissue increased upon further treatment with the medicinal product according to the invention until approximately two weeks after the beginning of the therapy and filled up the ulcus. It was striking that already after the first days of treatment the surrounding of the ulcus calmed down, the erythema and the edema of the surrounding skin disappeared and also the edge of the ulcus was no longer edematous and miscolored in all of the patients. Histologically, cell-rich granulation tissue primarily consisting of fibroblasts and fibrocytes and exhibiting intensive new vascular formation and collagenous fiber formation and only a slight infiltration of inflammatory cells and tissue necroses on the surface was to be seen in all biopsies in the second week of treatment. Epithelization of the skin defects after the third week of treatment started from the edges of the wound and could then also be detected histologically by the second biopsies in the fifth week of treatment. In the further course of treatment, the size of the ulcera declined due to epithelization, but also to cicatricial shrinkage. With the exception of patient 5, they were scarred over in the 12th week of treatment at the latest.

The results indicated above demonstrate that the topical use of the medicinal product according to the invention promotes wound healing and, thus, is able to completely cure chronically non-healing cutaneous ulcera in patients treated by conservative therapies for at

least six months without success and, thus, offering extremely poor prognoses for wound healing.